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Capabilities

- Motivating model: multielement array, noiseless environments
- Extension to noisy environments
- **Extension to other linear processor structures**

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Extension to Other Linear Processing Structures

- Linear excision usable whenever multiple emitters received over linearly independent channels
  - Space-time adaptive processors (STAP)
  - Polarization diverse receivers
- Linear excision can also be used to separate baseband symbol sequences if the modulation format induces significant conjugate or spectral redundancy on the output waveform
  - Conjugate-redundant BPSK and GMSK signals
    - 1 Msps 802.11
    - GSM, Bluetooth
  - Modulation-on-symbol direct-sequence spread spectrum signals
    - 1 Msps and 2 Msps DSS 802.11 PHY's
    - UMTS with short scrambling code
  - Frequency-diversity spread spectrum signals (e.g., stacked carrier spread spectrum)
- Latter approach leads to linear single-antenna interference excision techniques using RAKE filtering structures or OFDM subcarrier combinings
  - Adaptive demodulation and code-nulling processors (Agee, 1988, 1993)
  - Linear MMSE techniques (Honig and Madhow, 1994)
- Can also greatly increase linear excision capability of spatial processors
  - Degree-of-freedom increase
  - Additional separation on basis of range (TOA), Doppler (FOA), or code

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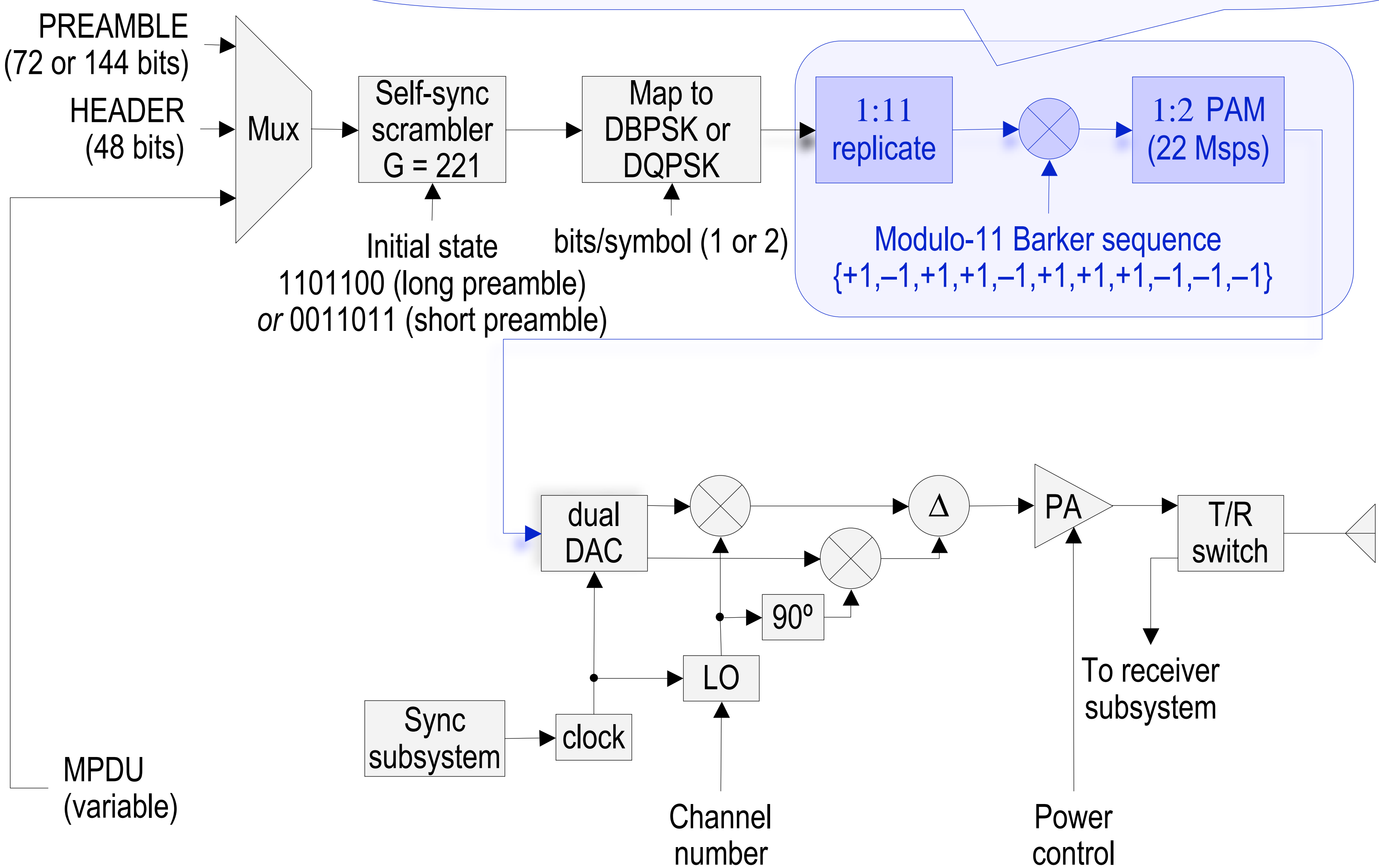
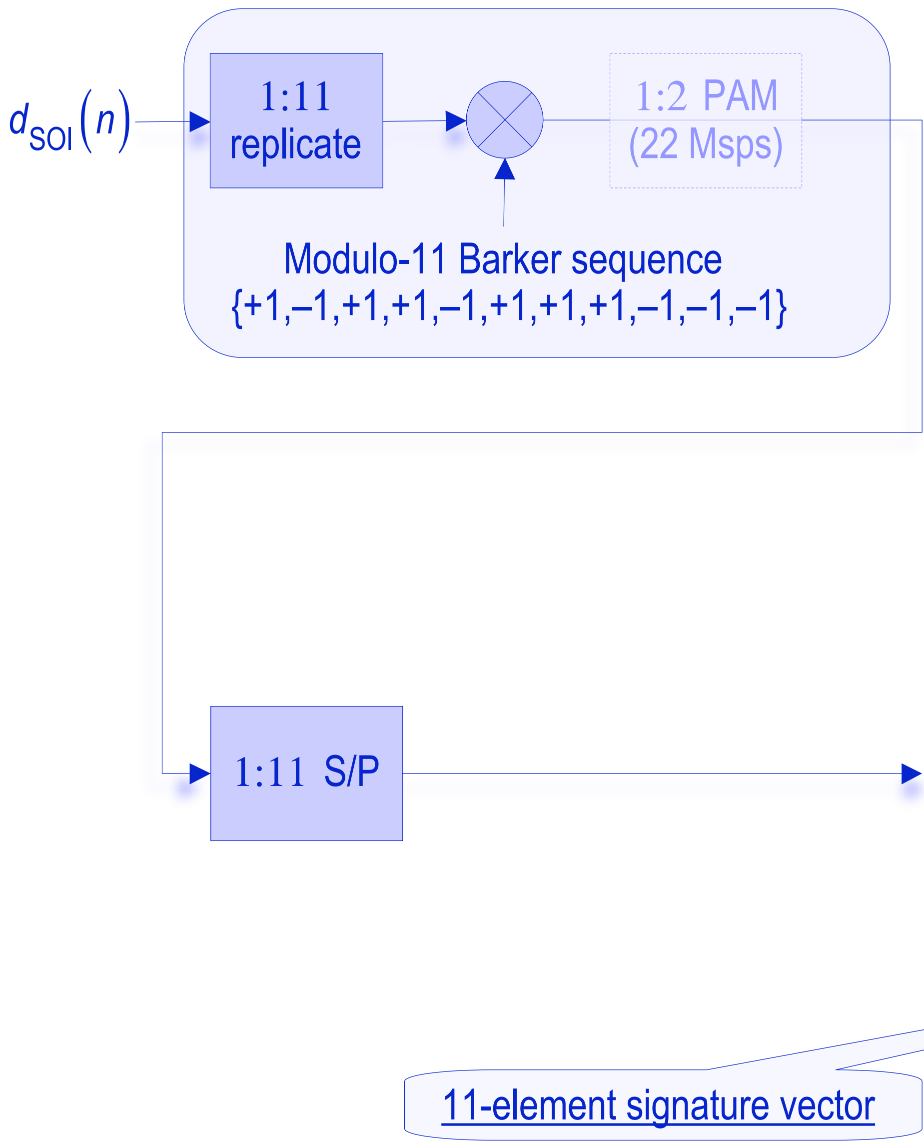
Example Modulation-on-Symbol DSSS: 1 Msps and 2 Msps (DSS) 802.11 PHY

- Code period = spreading factor (equivalently, modulates each symbol
- Equivalent to 22-element wideband (dispersive) antenna array



DSS Transmit Signal (Chip Modulation Ignored)

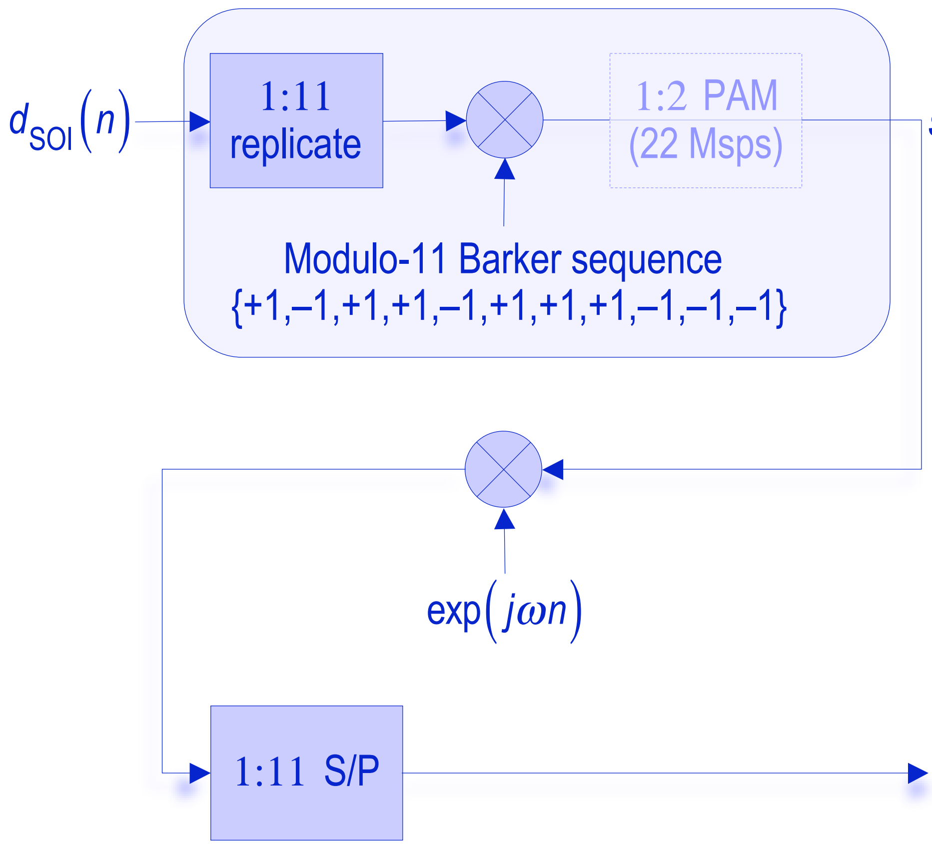


$d_{\mathrm{SOI}}(n)$

$$s_{\mathrm{SOI}}(n) = c(n \bmod 11)\, d_{\mathrm{SOI}}(\lfloor n/11 \rfloor)$$

$$\mathbf{s}_{\mathrm{SOI}}(n) = \begin{pmatrix} s_{\mathrm{SOI}}(11n) \\ \vdots \\ s_{\mathrm{SOI}}(11n+10) \end{pmatrix} = \begin{pmatrix} +1 \\ -1 \\ +1 \\ +1 \\ -1 \\ +1 \\ +1 \\ +1 \\ -1 \\ -1 \\ -1 \end{pmatrix} d_{\mathrm{SOI}}(n)$$

Effect of Frequency Shift (Chip Modulation Ignored)



$$s_{\text{SOI}}(n) = c(n \bmod 11)\, d_{\text{SOI}}(\lfloor n/11 \rfloor)$$

$$\mathbf{s}_{\text{SOI}}(n) = \begin{pmatrix} +1 \\ -e^{j\omega} \\ +e^{j2\omega} \\ +e^{j3\omega} \\ -e^{j4\omega} \\ +e^{j5\omega} \\ +e^{j6\omega} \\ +e^{j7\omega} \\ -e^{j8\omega} \\ -e^{j9\omega} \\ -e^{j10\omega} \end{pmatrix} d_{\text{SOI}}(n)\, e^{j11\omega n}$$

<u>Still</u> an 11-element signature vector

FOA added to baseband symbol sequence

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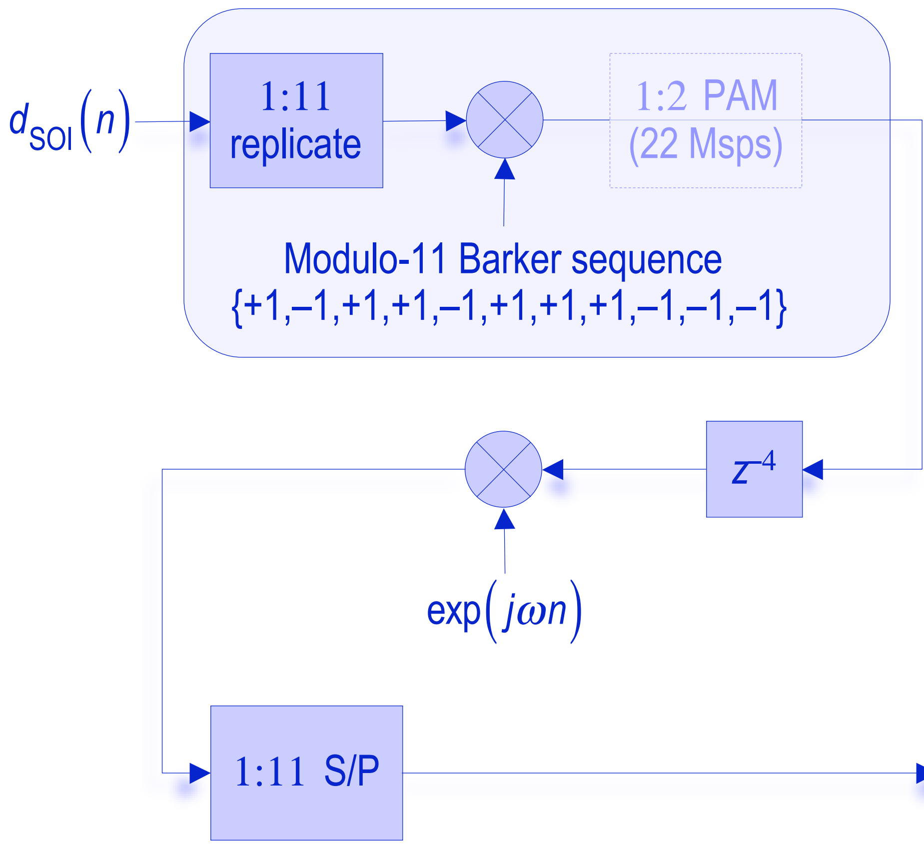
Effect of Delay and Frequency Shift (Chip Modulation Ignored)



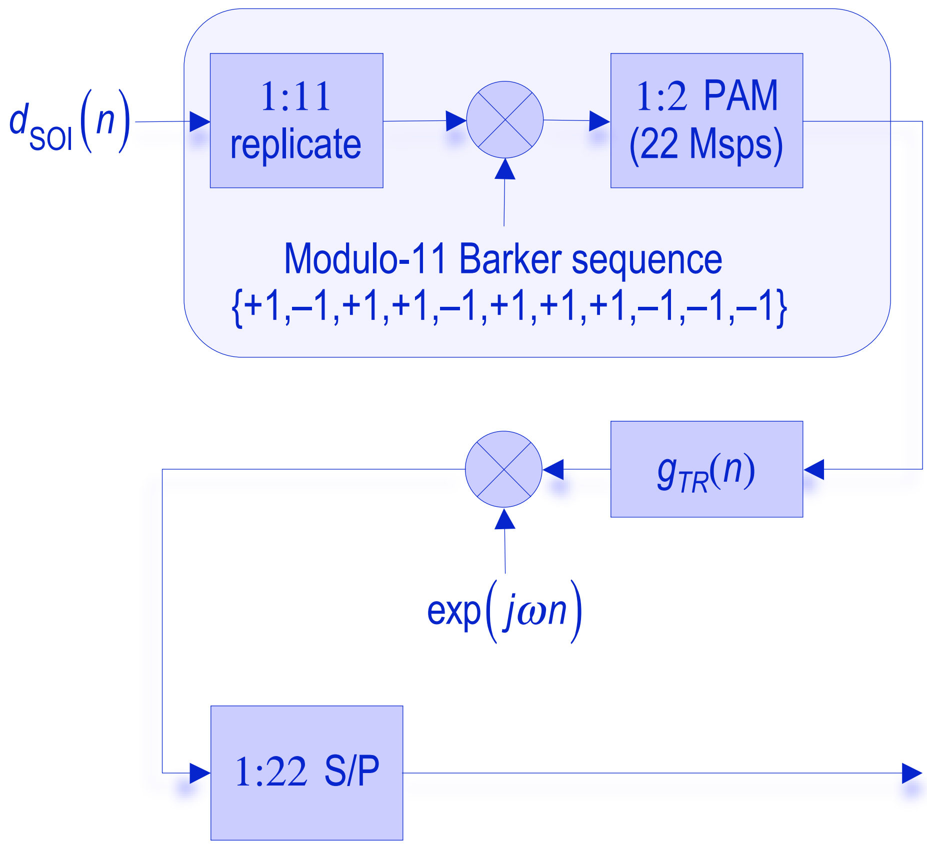
$$s_{\text{SOI}}(n) = c(n \bmod 11)\, d_{\text{SOI}}(\lfloor n/11 \rfloor)$$

$$\mathbf{s}_{\text{SOI}}(n) = \begin{pmatrix} +1 & 0 \\ -e^{j\omega} & 0 \\ -e^{j2\omega} & 0 \\ -e^{j3\omega} & 0 \\ 0 & +e^{j4\omega} \\ 0 & -e^{j5\omega} \\ 0 & +e^{j6\omega} \\ 0 & +e^{j7\omega} \\ 0 & -e^{j8\omega} \\ 0 & +e^{j9\omega} \\ 0 & +e^{j10\omega} \end{pmatrix} \begin{pmatrix} d_{\text{SOI}}(n-1) \\ d_{\text{SOI}}(n) \end{pmatrix} e^{j11\omega n}$$

11×2 signature <u>matrix</u>

Time-dispersion added to baseband sequence

Effect of Chip Modulation and Channel Dispersion



$$s_{\mathrm{SOI}}(n) = \sum_m c(m \bmod 11)\, d_{\mathrm{SOI}}(\lfloor m/11 \rfloor)\, h_{\mathrm{chip}}(n-2m)$$

$$= \sum_m d_{\mathrm{SOI}}(m) \left(\sum_{k=0}^{10} c(k)\, h_{\mathrm{chip}}(n-2(11m+k)) \right)$$

$$= \sum_m d_{\mathrm{SOI}}(m)\, h_{\mathrm{sym}}(n-22m)$$

$$h_{\mathrm{sym}}(n) \triangleq \sum_{k=0}^{10} c(k)\, h_{\mathrm{chip}}(n-2k)$$

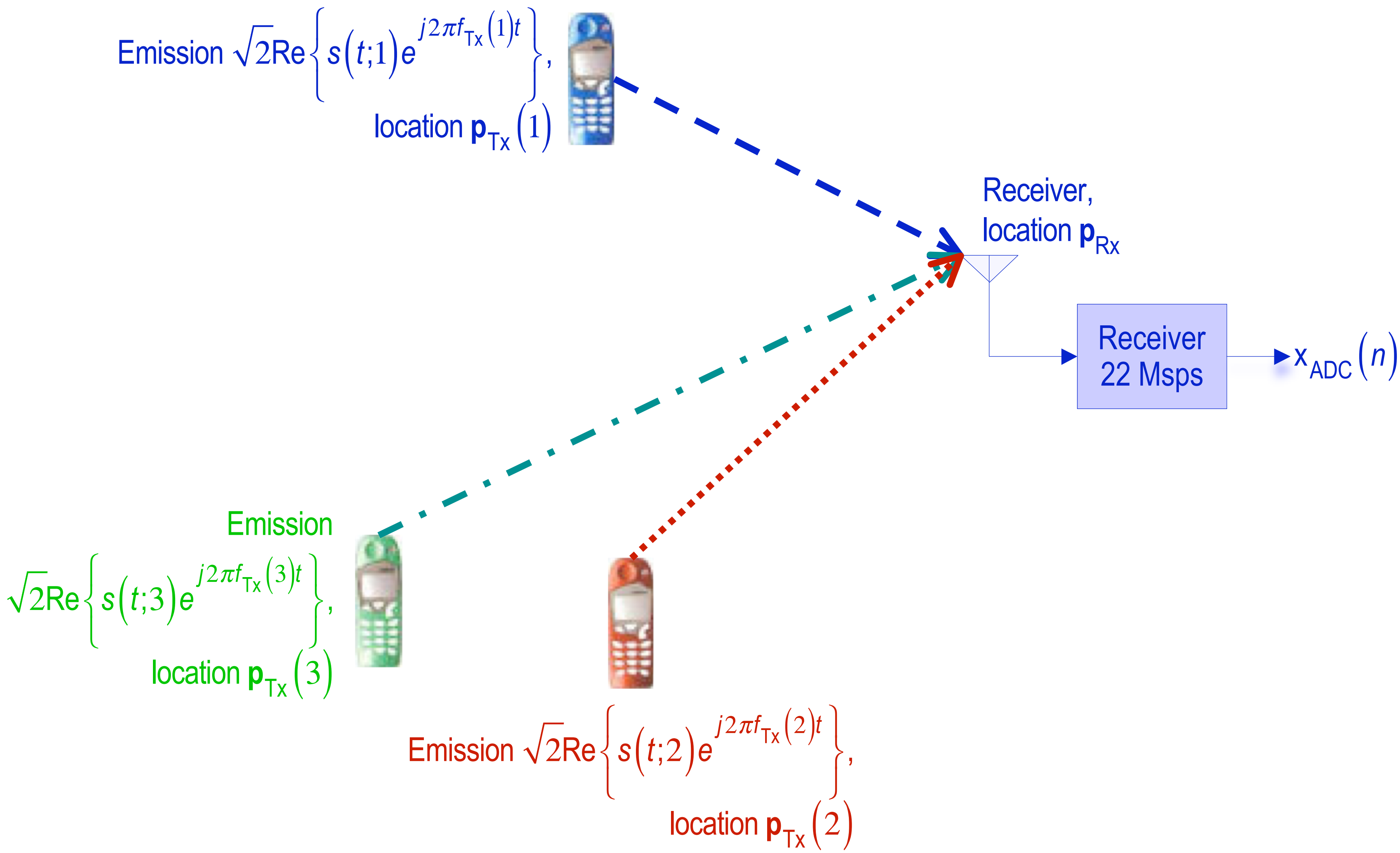
$$\mathbf{s}_{\mathrm{SOI}}(n) = \mathbf{h}_{\mathrm{TR}}(n) \otimes \left(d_{\mathrm{SOI}}(n) e^{j22\omega n} \right)$$

$$\left(\mathbf{h}_{\mathrm{TR}}(n) \right)_k = h_{\mathrm{TR}}(k+22(n-m))\, e^{j\omega k}$$

$$h_{\mathrm{TR}}(n) = g_{\mathrm{TR}}(n) \otimes h_{\mathrm{sym}}(n)$$

22×1 dispersive signature <u>operator</u>

Multiple DSS Emitter Environment



Received Signal Model After 1:22 Serial-to-Parallel Conversion

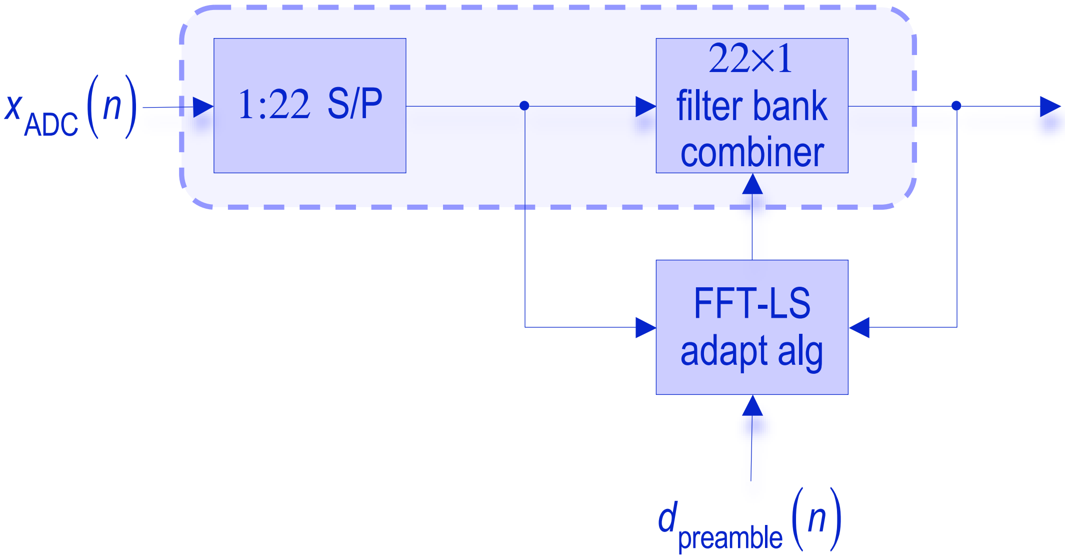
$$x_{\text{ADC}}(n) \longrightarrow \boxed{1{:}22\ \text{S/P}} \longrightarrow \mathbf{x}_{\text{SP}}(n) = \boldsymbol{\varepsilon}_{\text{SP}}(n) + \sum_{\ell=0}^{L_{\text{emit}}-1} \mathbf{h}_{\text{TR}}(n;\ell) \otimes \left(d(n;\ell) e^{j2\pi\alpha_{\text{TR}}(\ell)n} \right)$$

$$= \mathbf{h}_{\text{SOI}}(n) \otimes \left(d_{\text{SOI}}(n) e^{j2\pi\alpha_{\text{SOI}}n} \right)$$

$$+ \left(\boldsymbol{\varepsilon}_{\text{SP}}(n) + \sum_{\ell=1}^{L_{\text{SNOI}}} \mathbf{h}_{\text{SNOI}}(n;\ell) \otimes \left(d_{\text{SNOI}}(n;\ell) e^{j2\pi\alpha_{\text{SNOI}}(\ell)n} \right) \right)$$

- 22-element dispersive channel
  - 11 effective degrees of freedom within signal passband
  - 22 effective degrees of freedom over full signal band
- Linearly independent channel vectors if emissions received with different delays, frequency shifts
  - TOA and FOA ⇔ DOA with spatial processor
  - Allows rejection of interference based on range, velocity, or carrier (clock sync) differences
  - Additional separation allowed if codes different as well (e.g., UMTS with short scrambling code)

Example Interference Excision Processing Structure



$$\begin{aligned}\hat{d}_{SOI}(n) &= \sum_m \mathbf{w}_{SOI}^H(m)\mathbf{x}_{SP}(n+m) \\ &= \sum_m \sum_{k=0}^{22} \left(\mathbf{w}_{SOI}(m)\right)_k^* x_{ADC}\left(22(n+m)+k\right) \\ &= \sum_m \tilde{w}_{SOI}(m)\, x_{ADC}(22n-m),\end{aligned}$$

$$\tilde{w}_{SOI}(m) \triangleq \left(\mathbf{w}_{SOI}(-m \bmod 22)\right)^*_{\lfloor m/22 \rfloor}$$

- Up to 10 co-channel interferers excisable within signal passband
  - 21 excisable over full band (most important current application)
  - SNOI's separable on basis of TOA or FOA
  - Many adaptation algorithms available to train weights
  - Once trained, weights can be applied to remainder of signal (stationary background)
- Spatial interference excision results apply on a per-frequency basis
- Performance can greatly exceed matched-filter despreader, if SNOI's also DSS
  - More generally, if SNOI's have 1 Msps base rate (e.g., Bluetooth)

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Blind Separation Example: Overlapping MOS-DSSS (1988 DSP Workshop)

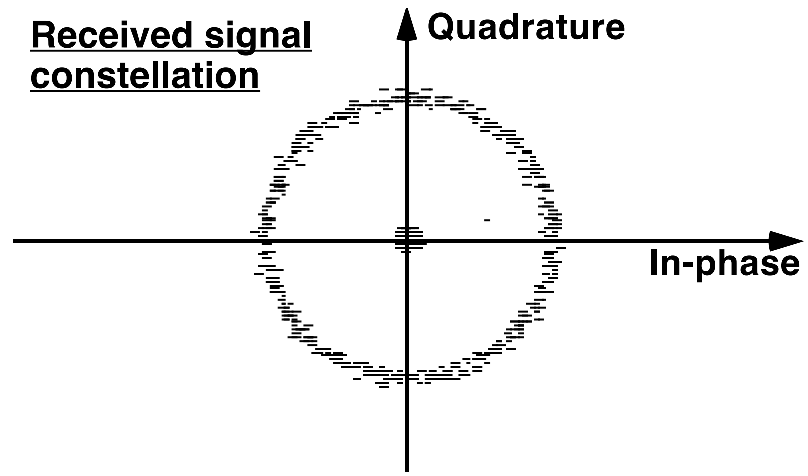
SOI Parameters

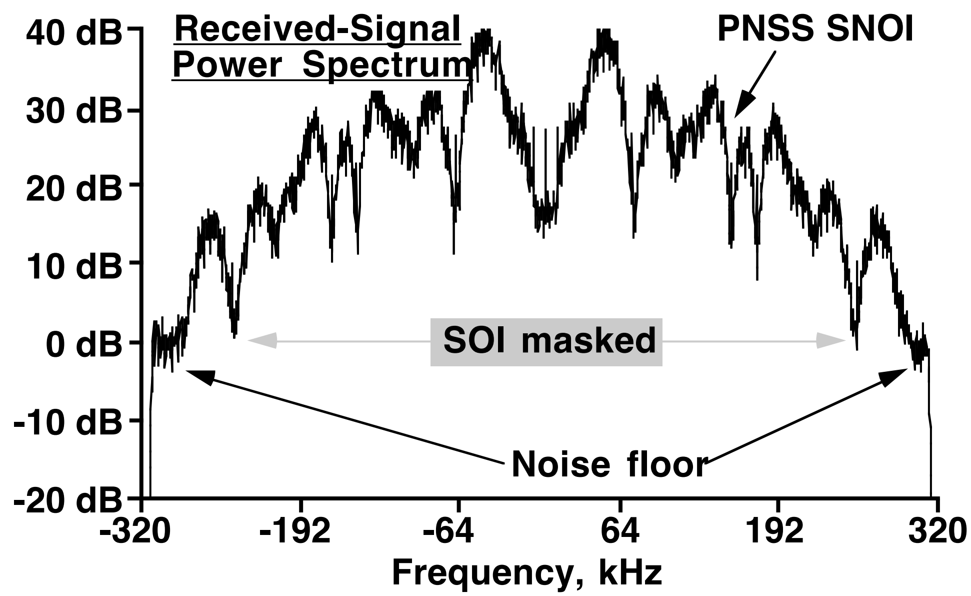
- 20 ksym/sec QPSK message seq.
- 320 ks/s QPSK spreading sequence
- 16-chip PN spreading code
- 100% Nyquist chip-shaping
- 0 dB received SWNR
- No timing or carrier offset

SNOI Parameters

- 20 kb/s BPSK message sequence
- 320 kb/s BPSK spreading sequence
- 16-chip PN spreading code
- 100% Nyquist chip-shaping
- 30 dB received SWNR (-30 dB SIR)
- 15-chip timing offset
- 32 kHz carrier offset

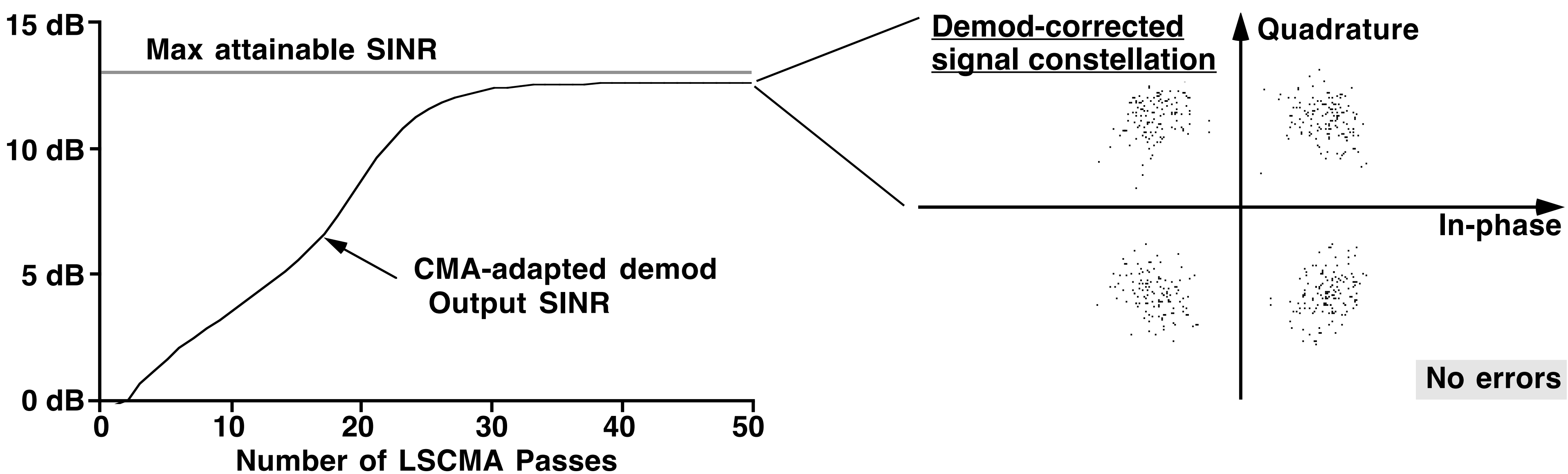
Matched filter fails
(MF output SINR = -17 dB)





Excision Performance

- 1 kbaud (16 kchip) collect
- 32 samples per baud (2 samples per chip)
- 64-tap FSE demodulator
- Static LSCMA blind adaptation algorithm



Example: Stacked-Carrier Spread Spectrum

- Developed 1994-1996 for covert LPI/AJ airborne communications (Backtalk system)
- Goal to fully integrate adaptive arrays with spread spectrum modulation
  - Maintain <u>full advantages</u> of wideband spreading (frequency selectivity, narrowband jammer suppression)
  - Add <u>full advantages</u> of adaptive spatial processing (especially linear interference excision)
  - Eliminate problems associated with both technology classes
  - Provide ancillary benefits associated with USAF problem(s)
- Led to stacked-carrier spread spectrum (SCSS) modulation format
  - Direct spreading over discrete frequency channels
  - Implementation using TDD-OFDM/multitone processing structures
  - Array-like adaptive excision of other SCSS links as part of the despreading process
  - Adaptive processing at all nodes in network (adaptive link optimization)
  - Seamless extension to spatial Tx/Rx processing
    - » Fully-adaptive combining over all available diversities (spatial, spectral, polarization)
    - » Unchanged transmit/receive adaptation, sync/timing recovery algorithms
    - » Baseband directly recovered — eliminates dispersive effects due to wide spread BW
- Incorporated into (original) TDD variant of AT&T WLL for Angel program (1995-1997)
  - Reference US Patents 6,128,276 (Backtalk) and 6,359,923 (Angel)

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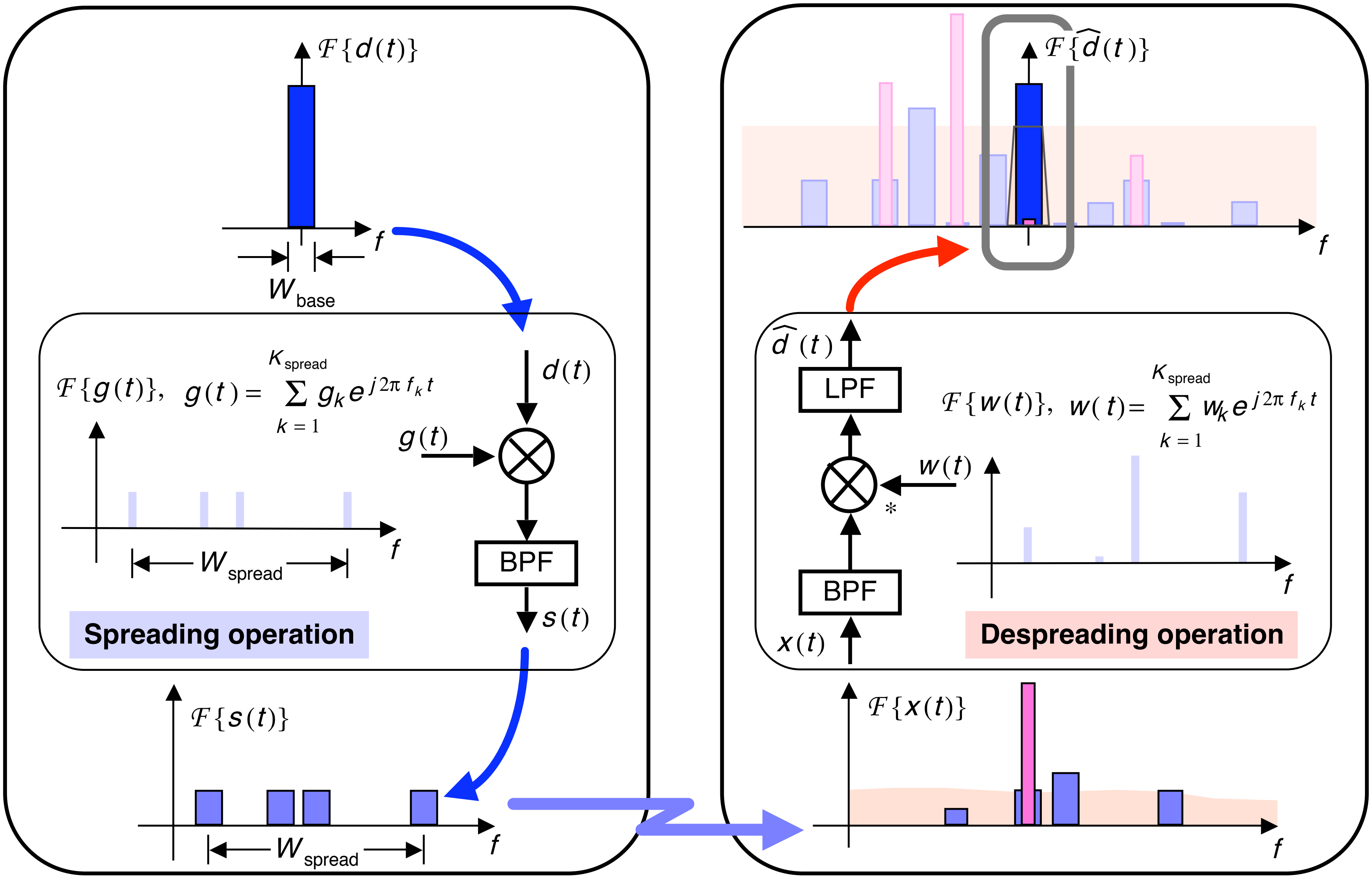
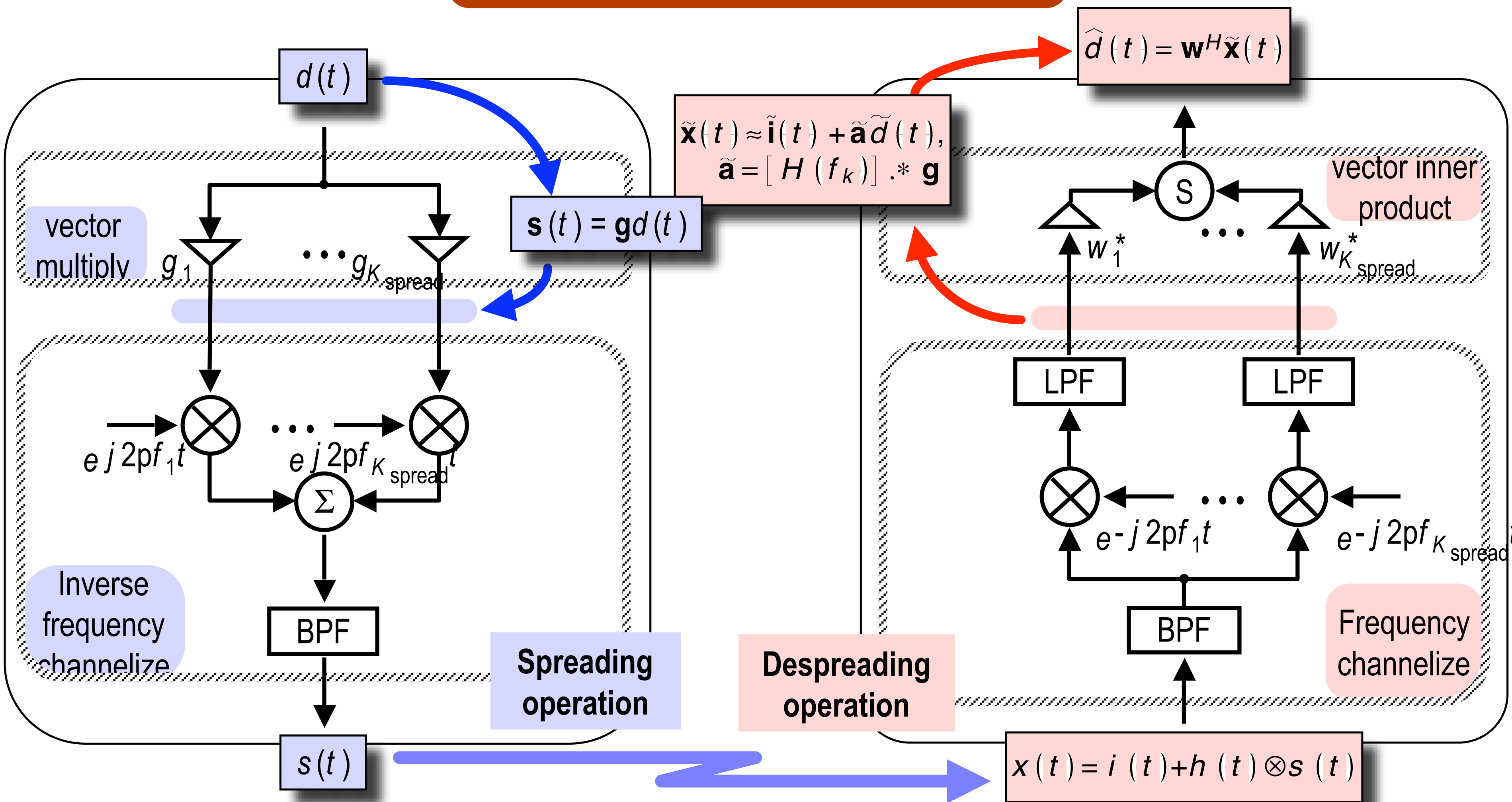
Stacked Carrier Spreading/Despreading Concept



Frequency Channelizer Based Implementation

Antenna array analogy
Equivalent dimension K_{spread}
Equiv. BW $= W_{base}$ (narrowband array)



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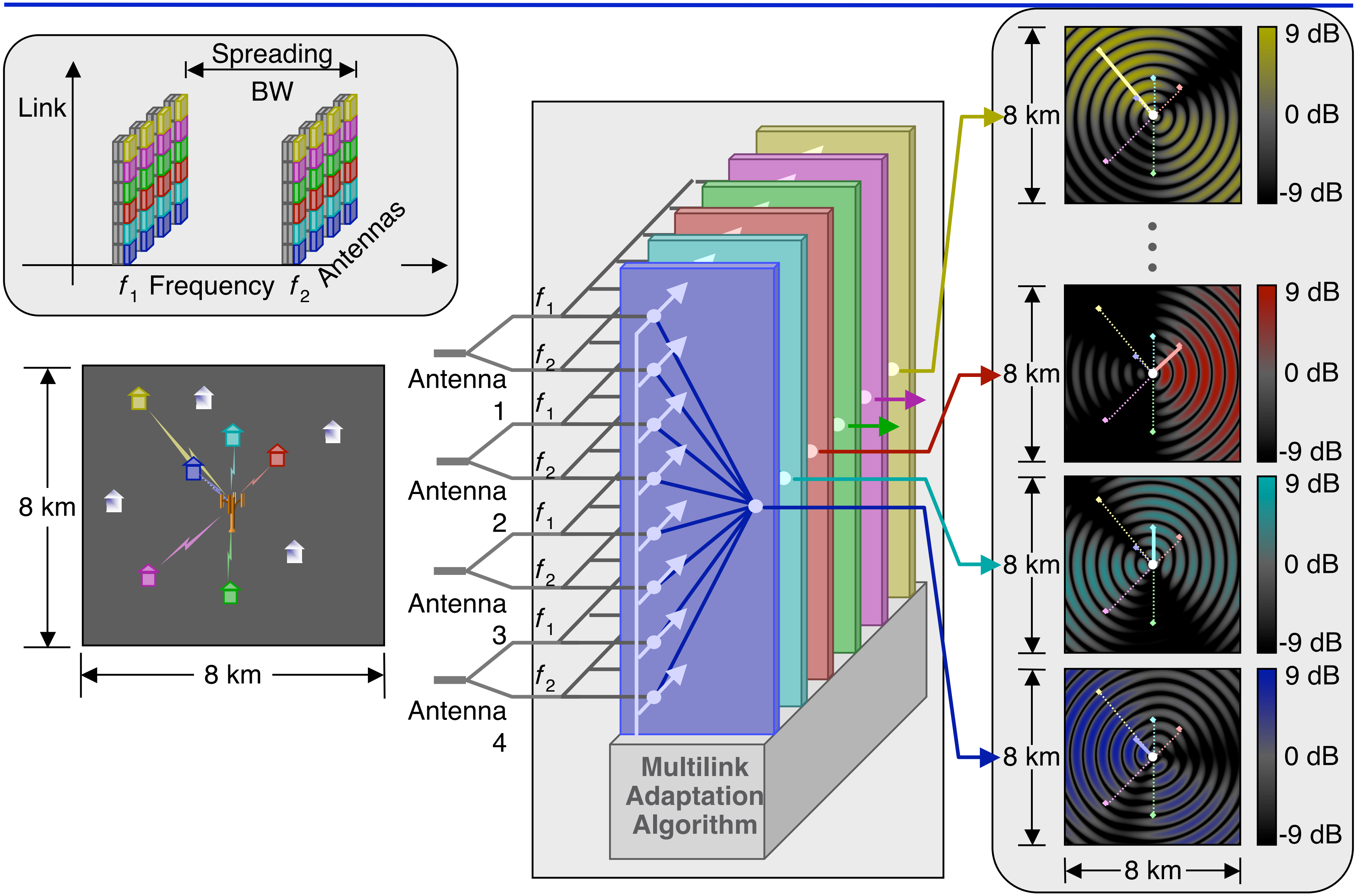
Integrated Spatial and Spectral Despreader (SCSS and Multielement Antenna Arrays)



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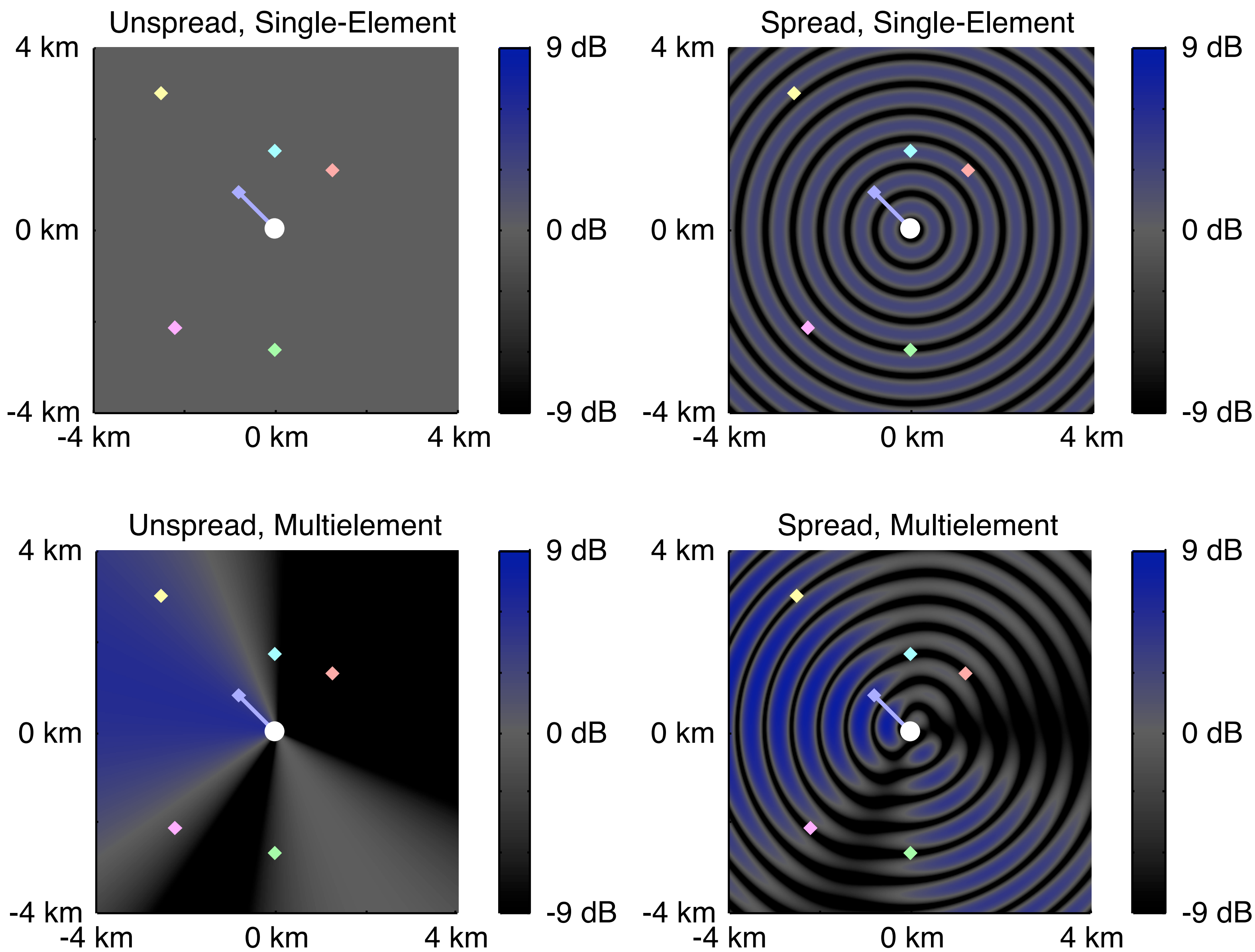
Link 1 Gain Intensities, Common Spreading Code



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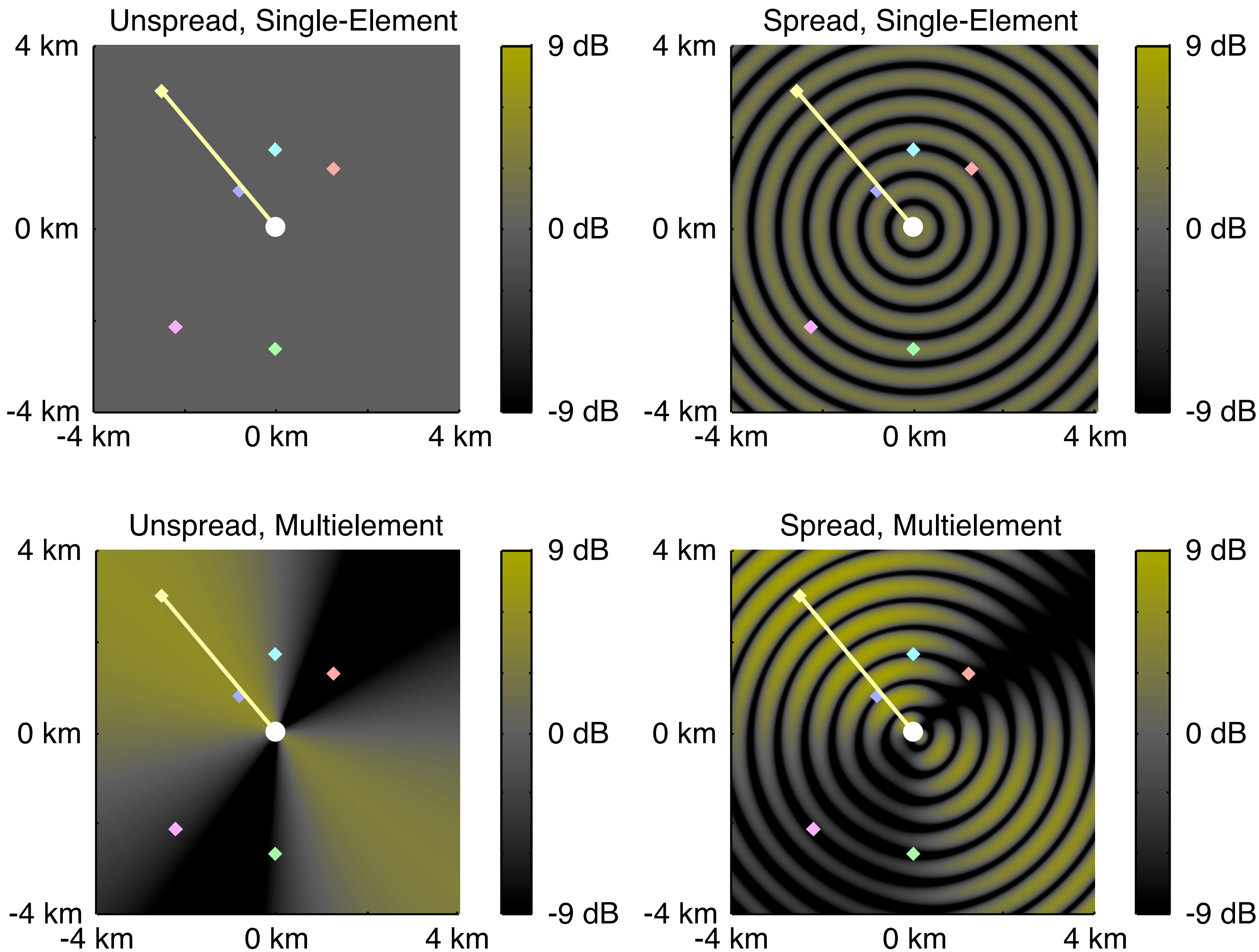
Link 6 Gain Intensities, Common Spreading Code



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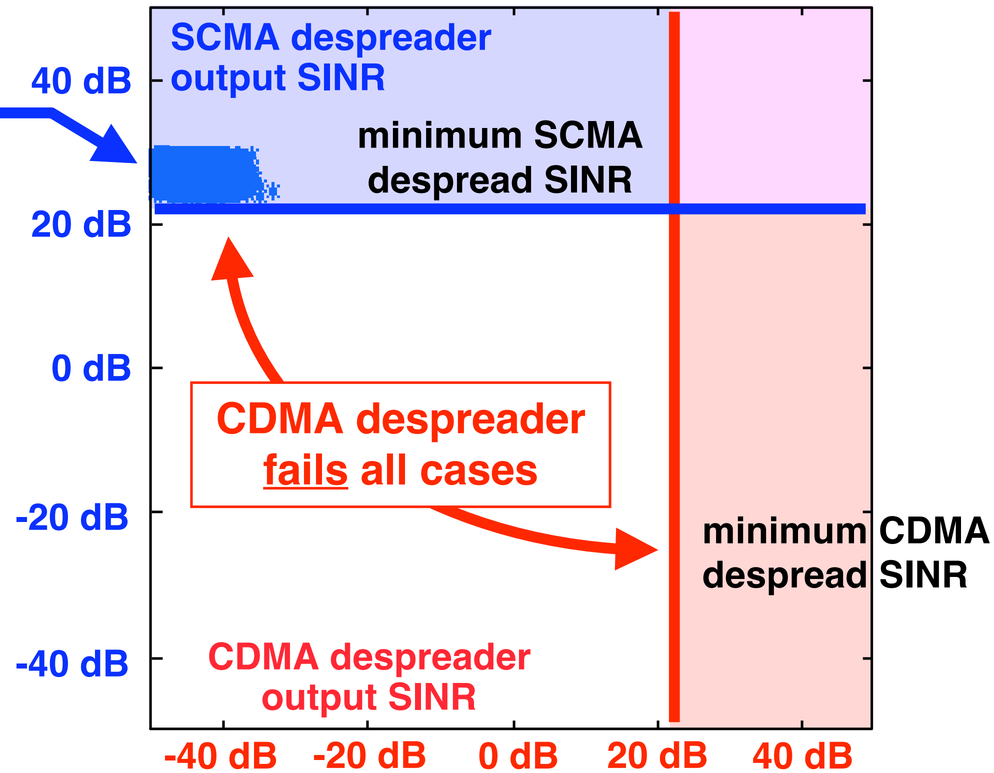
Example Code Nulling Capability: Fully-Loaded SCMA Network, Random Spreading Codes

Multiple Access Spreading, Despreading Parameters

Spreading factor	**=**	**16**
Number of users	**=**	**16 (fully loaded network)**
Required despread SINR	**=**	**24 dB (6 bits/symbol w/ ECC)**
Input SWNR Range	=	24-30 dB, randomly varied each link
Number of MA trials	=	200 (16×200 = 3,200 spreading codes)
Spreading codes	=	Random (nominal uplink signals)

- **16 SCMA users supported**
- **1 CDMA user supported**

SCMA despreader succeeds all cases!



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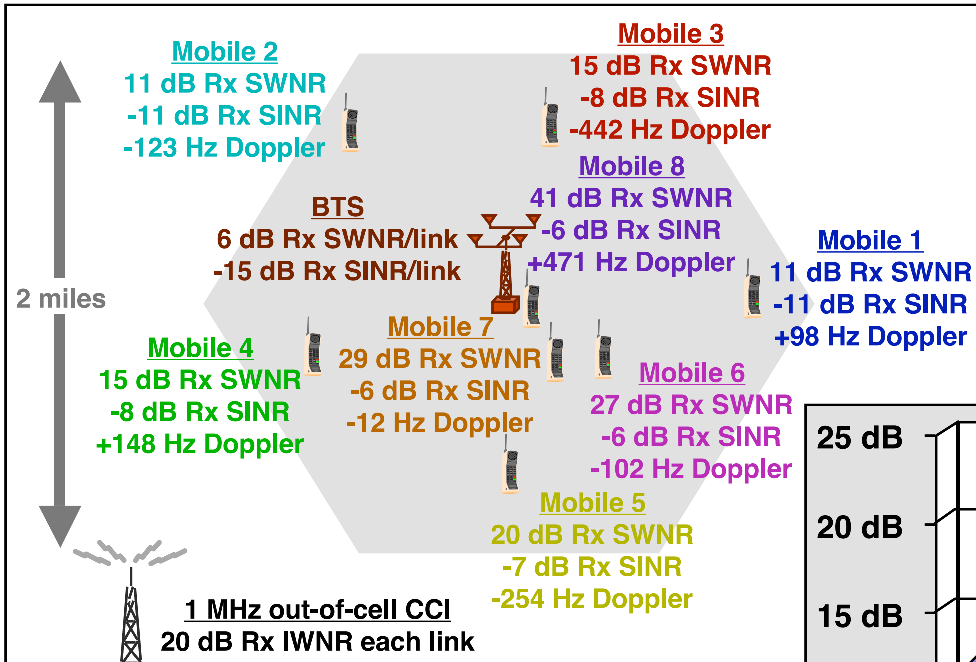
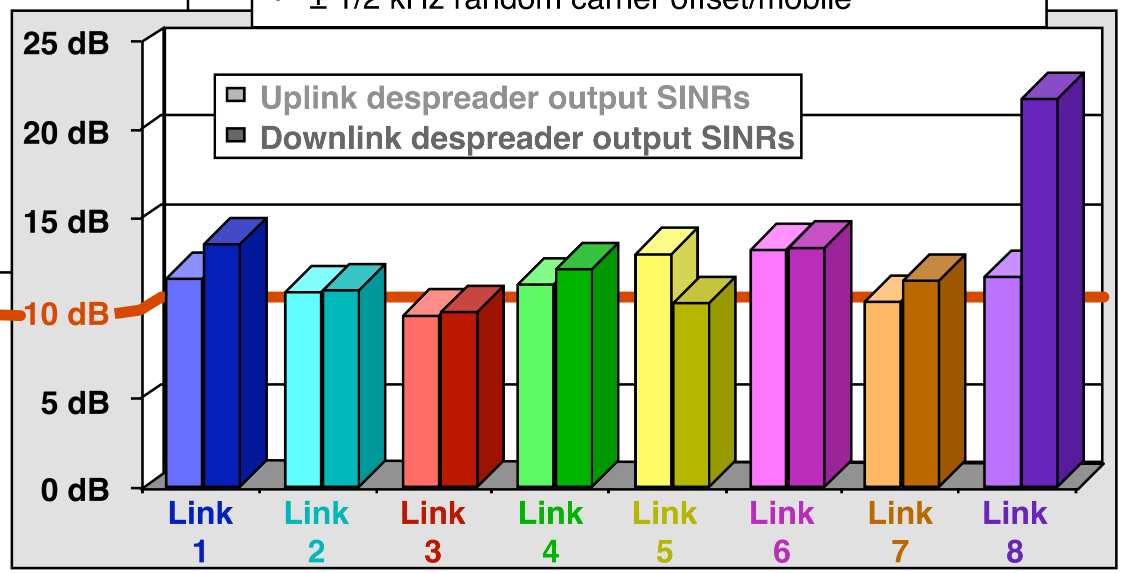
Eight-Mobile Multiple-Access Demonstration



- 4 spreading frequencies (supports 1 CDMA user at 10 dB required despread SINR, 4 dB input SINR)
- Strong co-channel interferer, 20 dB Rx IWNR/link
- 4 omni antennas at BTS, 1 omni/mobile
- 8 co-channel links, 384 kbps full-duplex traffic rate
  - -15 dB Rx SINR/link at BTS
  - -11 dB to -6 dB Rx SINR/link at mobiles
- ± 1/2 kHz random carrier offset/mobile



≥ 10 dB despread SINR each link

< 10^{-3} raw SER supported

No symbol errors in simulation!

Uplink despreader output symbols:

Downlink despreader output symbols: